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Anticipating Tomorrow's Maintenance Job

by

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Air Training Command

Anticipating Tomorrow's Maintenance Job

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Implications for the Air Force

Traditionally there has been a considerable lag between the time a new piece of equipment is introduced into the field for operational use and the time at which a supply of technicians trained to service and maintain the equipment becomes available. Since effective operational utilization of equipment is dependent upon adequate maintenance, this time lag is of serious concern.

This Research Review describes progress to date in a program of research directed toward developing procedures by means of which maintenance requirements of new equipment can be specified prior to the introduction of the equipment into operational use.

The procedures developed involve the establishment of maintenance requirements on the basis of prototype equipment and determination of the degree to which these maintenance requirements also apply to the operational equipment. Basic to this procedure is an analysis of what a man must do in order to check, adjust, trouble shoot, and repair equipment, or replace components. Information as to these requirements can be obtained through an analysis of the equipment itself and from analysis of such supplementary data as malfunction records.

The techniques which were developed were applied to the Q-24 prototype, and the information yielded compared with results of a similar analysis of the production model of the Q-24 used in the Strategic Air Command. The requirements for checking, trouble shooting, and for other aspects of the maintenance job down to the replacement of plug-in assemblies or "black boxes," established through analysis of *prototype* equipment, proved very similar to the requirements as established by application of the technique to operational equipment. This indicates that important progress could have been made in the training of Q-24 mechanics prior to the introduction of production models of the equipment. Definitive information was not obtained regarding the correspondence between prototype and production models with respect to requirements for repairing of equipment within the "black boxes." There is reason to believe, however, that, even with respect to these activities, training requirements could be established on the basis of analysis of the prototype.

This research also had other valuable outcomes. For example, an important requirement for the simplification of technical orders, with respect to terminology and form of presentation, became evident. The research also highlighted the importance of coordinating equipment design and job design at an early stage of equipment development. Effective equipment design must take into account the capabilities and the limitations of the human beings on whom effective operational use of the equipment depends. Another important outcome of the project was development of the "Standard Maintenance Form." This form provides a procedure whereby malfunction data can be recorded simply and in an organized fashion to yield a basis for meaningful analyses of malfunctions.

Although valuable by-products have been yielded, the major outcome of this research program concerns the prediction of maintenance requirements of operational equipment from prototype data. Research now in progress, and future research, will demonstrate whether specific and detailed maintenance job requirements can similarly be anticipated with other equipment. If these maintenance requirements can be predicted, the methods of job requirement anticipation developed in this research can be recommended as standard practice. If accurate anticipation of maintenance job requirements can be achieved, years of lead time can be saved whenever it is deemed desirable to take the "calculated risk" that the prototype equipment actually will go into production.

This Research Review will be of interest to training personnel, operational personnel, and military psychologists.

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Introduction

Frequently a considerable period elapses between the time a new equipment is sent into the field for operational use and the time at which technicians trained to service that equipment become available. This impairs operational utilization of the equipment until such time as adequately trained technicians are available. It is therefore highly important to develop procedures whereby maintenance requirements of new equipment can be specified prior to the introduction of the new equipment for operational use. This can make possible prior training of maintenance personnel and reduction of the time lag between introduction of new equipment and the availability of trained maintenance personnel in sufficient number to meet operational requirements. A contribution towards reaching this ideal can, of course, be made through simplification of the maintenance task.

The research covered by this report is directed primarily towards the *development of a method for anticipating maintenance job requirements* prior to the introduction of new equipment into the field.[1] The steps in the following section summarize what was done in arriving at a method for making such anticipations.

Preliminary Investigation

Initial Inquiry; Selection of an Equipment for Study

In this investigation of procedures for anticipating maintenance job requirements, it was felt necessary first to select an equipment or equipments which would be the focal point for the research. Although the primary concern eventually would be with *anticipating* maintenance job requirements for equipments which had not yet been built, it seemed at this stage that an existing equipment would provide a more concrete basis for the preliminary investigation. The Air Force suggested that airborne bombing-navigational equipment would probably offer a fruitful research area. In keeping with this suggestion, the AN/APQ–24 Radar Set, manufactured by Western Electric Company, and the K-1 Bombing-Navigational System, manufactured by Sperry Gyroscope Company, were selected for study. When this study was initiated, the Q-24 had been in use for some time longer than the K-1. The investigation was therefore started on the Q-24 in order to take advantage of the greater backlog of experience on that equipment.

It was thought desirable, after the particular equipment had been selected for a focal point, to gather as much information about the job of maintenance as could practicably be obtained. In particular, information pertaining to Q-24 maintenance was sought. On the basis of this preliminary information, it might be possible to develop more refined techniques of investigation, if such were required.

It seemed that one way to collect some of this information would be to study the records which had been kept of maintenance activities. Consequently, this possibility was investigated first.

Investigation of Maintenance Records

Visits were made to Air Materiel Command (AMC) and to the base at which advanced engineering testing of the Q-24 was being carried out. Maintenance records were studied in the hope that they would reveal the kinds of problems maintenance mechanics were required to solve. Moreover, it was hoped that some information might be gleaned from the records on *how* the mechanics solved these problems. A comparison of these two aspects of maintenance between prototype and production models would be one index of the degree to which maintenance job requirements could have been anticipated for the Q-24. It was found, however, that although some information was available on the malfunctions which had been encountered, these records provided no data on other aspects of the maintenance job. The general conclusions as to the limited usefulness of these records were confirmed by the reports of various maintenance officers. These conclusions were that the so-called "Unsatisfactory Reports" did not cover all malfunctions which developed in the course of engineering testing or in operations. Therefore, these reports could

[1] This report represents a summary presentation of material included in more extensive technical publications. Copies of these publications are available upon request (1, 2, 3).

not be trusted as being representative of maintenance problems. Secondly, the reports frequently omitted clear (or in fact, any) statements of symptoms. Usually the final corrective action or replacement made was all that was stated in the report. This is to some degree understandable since the principal basis for the report was to help the factory improve the design of the equipment.

In interviews with persons on these field trips it was suggested that the technical orders for the equipment might offer some clues for direction of the investigation. This source was therefore looked into next.

Technical Orders on the Q-24 Equipment

It was thought that study of the technical orders would provide more information on the structure, responsibilities, and problems of the maintenance job. Technical orders on the K-1 were not yet available at that time, but the technical orders for the Q-24 showed quite clearly, when studied in the light of what had been learned in interviews with personnel in the field, that the job of maintenance consisted of more than just finding troubles in a malfunctioning set. Much of the job apparently consisted of relatively routine activities such as checking the equipment for proper operation.

It seemed, therefore, that sufficient information had been collected to permit setting up a tentative outline of maintenance job activities at this time. This outline would help structure data collection and other research activities.

Defining the Maintenance Job

The first point which was established was that the project would be concerned only with the *technical* aspects of the job. That is, given an equipment and the necessary tools and test equipment, what must the maintenance mechanic do in order to perform his job? Other aspects such as the motivation of the mechanics, although critically important, were set aside.

Following the initial investigations in the field and preliminary study of the technical manuals, some definitions were more or less arbitrarily set up by the project staff. These definitions were intended to be exhaustive of the technical aspects of the maintenance job.

The first of these definitions was that of the maintenance job as such. The mechanic's technical job was defined as "finding out if the equipment is operating within tolerance limits, and locating and correcting the causes for out-of-tolerance operation." These tolerance limits are specified by the manufacturer and by various military agencies.

Within this more or less general definition, the functions of the job were defined. These are covered by: checking and adjusting, trouble shooting, replacing of components, and repairing of components. Formal definitions were prepared for each of these categories. The later analysis of job behaviors was to revolve around these job functions as they were defined. No new categories appeared from later investigation.

The preliminary analysis outlined above provided the groundwork for succeeding steps in this research. With an equipment selected for initial work, a preview obtained regarding what could be expected from maintenance records and technical orders, and the maintenance job tentatively defined, it was possible now to begin filling out the preliminary analysis.

Filling Out the Preliminary Analysis

Interviews with factory design engineers. Trips were made to the factories which manufactured these equipments. Interviews were held with the personnel who were intimately involved in the design, construction, recording of data, and other functions having to do with the prototype and production model development. Information and informed opinion were obtained as to the kind and extent of maintenance job behaviors which could be predicted from prototype equipment. The opinions expressed by different people tended toward wide divergence. These divergences were reconciled later in the course of the project as arising from different interpretations of the "maintenance job."

Study of existing training of electronics maintenance personnel. Visits were paid to various installations which trained maintenance mechanics for the AN/APQ-24 and K-1 jobs in an effort to determine what were the sources of job data used in setting up the training programs. These visits included factory training establishments and Air Training Command installations. Some inquiry was also conducted into on-the-job training in the Strategic Air Command. Course syllabuses and other printed material used in training were obtained. Inquiry was made at Headquarters Air Training Command, Keesler AFB, and Lowry AFB as to how training requirements were obtained by ATRC, and from what job behavior data the curricula were established and training criteria set up. The responsible persons interviewed expressed regret that they could not provide useful information as to the sources of such data and disappointment over the fact that no such sources seemed available.

Collecting of malfunction records at Air Proving Ground. Several visits were paid to the Air Proving Ground in an effort to learn more about what happened during operational suitability testing in view of job anticipations. Characteristic procedures were set down. Copies of malfunction records were obtained, but like the records at AMC, they seemed to lack completeness of coverage (malfunctions considered minor from the standpoint of equipment modification tended not to be recorded) and individual reports lacked important behavioral data.

Visits to Strategic Air Command bases to study on-the-job activities. Two SAC bases were visited for several weeks each. Each of these bases had some electronic equipment of the type under study. On-the-job activities were observed directly; a study was made of types of job assignments given to various echelons of maintenance, and methods of getting malfunction records were noted. Copies of malfunction records were made for later analysis at the American Institute for Research. Information and opinion were obtained by extensive interviews with personnel from commanding officers to airmen.

Although the distinction between echelons of maintenance (such as flight line vs. shop levels) was fairly well established, assignment of individuals was by numerical need rather than by kind or level of training. For example, individuals were found working in the shop who had been trained only for the job of *checker* at the flight line level of maintenance, according to then-existing policy. Interviews indicated that trouble shooting was generally more trial-and-error than systematic. Attempts here, as in the ATRC installations, to obtain a set of systematic trouble-shooting techniques were met by some variation of the statement: *A good trouble shooter has to have "experience," and has to "know" his equipment.* Further attempts to pin down the behavioral variables in what was meant by "experience" and "knowing the equipment" led to paraphrases of the original statement as quoted.

Utilization of Maintenance Records

As mentioned in the previous paragraphs, maintenance records in existence at the time of this investigation did not contain the behavioral data needed for this research. In view of the dissatisfaction with maintenance records felt not only by American Institute for Research personnel but by many key persons dealing with this equipment, the development of a new reporting form was undertaken. Many responsible persons connected with both design and maintenance of airborne electronic equipment had agreed that a systematic, standardized method of reporting maintenance activities would be valuable in improving future maintenance as well as providing the job behavior data required for this research.

Development of a Standard Maintenance Form

In view of the dissatisfaction with malfunction records, felt not only by the research personnel but by many key persons dealing with this equipment, the development of a new reporting form was undertaken. This new report form came to be known as a Standard Maintenance Form (SMF). It was intended to be "standard" for a given equipment, although most of the categories included in this form were believed to be relevant to any electronic equipment and to some mechanical equipment. The form was based on an analysis of the information needed in getting to know about the mechanic's job as well as about the equipment and operations. It was expected to require a minimum of writing while getting a maximum of clearness and detail as to what happened in every maintenance incident. Maintenance activity analysis based on these SMF reports would tell the kinds of trouble which came up, the final corrective action, and some of the steps in between. It would also direct attention to problem spots in the equipment and indirectly to problems in carrying out the maintenance job. (A sample Standard Maintenance Form is presented in Appendix A.)

A detailed set of purposes and a rationale was prepared for the SMF. In the rationale each item or category was related to one or more purposes, and a discussion was given as to how the data obtained would serve that purpose (1).

Tryouts of the Standard Maintenance Form

After several preliminary revisions, the SMF was tried out at Hunter, Castle, and Carswell Air Force Bases. It was also used briefly at Eglin AFB. The form and its purposes were endorsed by persons of staff responsibility, and the form demonstrated that it could provide more useful information than any other record system seen to that date. It became clear, however, that the consistent use of a new record system, no matter how useful it might be, requires a program of indoctrination, training, and monitoring. This program seemed outside the scope and resources of this project. Nevertheless, the SMF can be recommended as a sound principle in data gathering for operations research.

Important as SMF data may be as supplementary information, it was found in a later phase of this research that other procedures can provide job anticipation data with less expense and effort. This conclusion becomes all the more strengthened when the original premise of trouble shooting by frequency or "probabilities" is replaced by the sounder procedure of trouble shooting by logical elimination. (See the section entitled "Trouble Shooting" for a fuller discussion of this topic.)

An Alternative to Maintenance Records

It was apparent that if a job anticipation procedure were developed which depended upon maintenance records for its data, application of that procedure would be difficult. Furthermore, even with the standardized reporting on the Standard Maintenance Form, the behavioral detail required for a comprehensive analysis of the job was lacking. These considerations led to a reassessment of the approach which had been taken.

The first point which came up was the distinction between the various levels of maintenance. This problem had been given very brief consideration earlier. The observation of operations in the field led to revision in thinking on the division of the maintenance job. This division is discussed in the section which follows.

Development of Distinctions Between Flight Line and Shop Maintenance

Existing policy split the flight line job into that of *system checker* and *system analyst*. The man who worked in the shop was called a *component specialist*. The split of line maintenance into two jobs seemed impractical in view of field conditions. The critical distinction, however, seemed to lie between line maintenance which involves working down to the "black box" level and shop maintenance which involves work within the "black box." Since this distinction is an important one for this research, it deserves some amplification.

A combination of logical analysis of the equipment as a system plus the study of field practices showed that the job requirements of mechanics who did checks and adjustments and trouble shooting in the aircraft on the flight line differed importantly from the pattern of job requirements of shop mechanics. The sharpness with which this distinction between line mechanics and shop mechanics is made differs from base to base. However, the distinction appears useful. In general, on the flight line the mechanic works down to the plug-in assembly. If he cannot bring a plug-in unit into specified tolerance, it may be replaced with a good one from the shop. If this line-shop distinction is maintained he does not trouble shoot within this assembly. Therefore, as a minimum requirement for this line activity he needs to "know" and work with the equipment only at the block diagram level. The block diagram shows how the various plug-in units or black boxes tie in with each other.

To work within the assembly a different set of knowledges and skills is called upon. This may require working with circuit diagrams and soldering and unsoldering wires within the plug-in assemblies in order to test resistors, condensers, and other parts. This *shop* activity, involving check and trouble-shooting procedures, does not usually parallel the somewhat more standardized activities which are a major portion of the *line* maintenance job as defined above. Although this distinction may not be made uniformly at all bases, it is very useful in the further consideration of equipment analysis and the prediction of maintenance requirements.

These considerations would indicate that the decisions of the design engineer about the basic plug-in assemblies are critical ones to the anticipation of the job of maintenance and the level of training and skill required *on the line*, as defined in the preceding paragraph. In other words, it seems possible that the line level maintenance job could be anticipated with greater success than could the shop level job when the anticipation is based on prototype equipment. This hypothesis accounts for some of the divergences of opinion expressed earlier on the practicality of anticipating maintenance job requirements from prototype equipment.

Distinguishing between line and shop levels of maintenance helped lay the groundwork for the development of the method of *equipment analysis*. Since the activities of the humans in the man-machine system of maintenance, as reported in maintenance records, were inadequate for the task at hand, it seemed reasonable to turn to the machine part of the team. The study of human activities was called *activity analysis*. Study of the maintenance job requirements from the viewpoint of the equipment was called *equipment analysis*. This latter technique, which has yielded very satisfactory results, is discussed in the following section.

Equipment Analysis as a Technique

Activity analysis of maintenance behavior on prototype equipment even under ideal conditions left large parts of the job unknown. The routines of checking, adjusting, and aligning, the detailed steps to be taken in replacing parts of the equipment, were not spelled out. The mental processes leading to decisions in efficient trouble shooting and correcting of malfunctions were not effectively covered. An additional technique of getting job information would, in any event, be necessary.

The solution was based on a method of man-machine systems analysis which is summarized briefly in Appendix B.[2] This technique, equipment analysis, was based upon *the demands made by the equipment* on the mechanic.

These demands may be grouped under two broad headings: (1) *what information does the machine provide*? (This element requires that the mechanic be able to *read* the indicators which present this information.) (2) what must the mechanic *do* to the equipment to get it to operate correctly within the specified tolerances? These two aspects are interdependent. Therefore, what the mechanic has to *see* (or *hear* or *feel*) and *interpret* was matched with the specific things he had to *do*. In the cases where he might have to choose or decide what to do, the alternatives were specified. Finally, it was necessary to specify what tells the mechanic that what he has done is correct or incorrect after he has performed a given action.

In specifying the signals, or cues, which the mechanic may observe and the actions and decisions he must make, there are a number of degrees of specificity which may be used. This research, it may be remembered, was concerned with specifying job requirements for purposes of training. It was thought, therefore, that considerable detail should be presented in the analysis. Consequently, after the tasks had been named which were appropriate to the job being studied, a detailed statement of each action, decision, and perception required to perform these tasks was made. In a recent analysis of this kind, over 3000 such behaviors were written.

Since such a large number of activities must be written for the analysis of a single job such as line mechanic for a given equipment, it was necessary that this writing be standardized. For this purpose the Job Behavior Form was devised, which provides a consistent format for the recording of job behaviors. A sample page from a Job Behavior Form is presented in Figure 1.

Actually, of course, the analysis of an equipment as complex as a radar bombing system includes a number of phases not mentioned above. The interested reader is reminded that a summary of the entire scheme of "functional analysis" is presented in Appendix B.

This step-by-step analysis of job activity requirements seems like a cumbersome procedure. Such detailed analysis tends to guarantee, however, that little of importance will be overlooked or taken for granted. Later paragraphs mention other advantages from this procedure.

The job data can be filled in by inspecting the equipment itself, or from specifications of that equipment, with the help of the engineers who can interpret its actions and functions. The check points and values, adjustments, and other features of construction are translated into human inputs and outputs of information "going into the mechanic" and responses or response alternatives, which should "come out of him." What is called "equipment analysis" can be done at the prototype stage of development of new equipment.

[2] A somewhat fuller presentation of man-machine task analysis was made by Robert B. Miller in a paper presented to the American Psychological Association meeting in September 1952. Modifications of the techniques are being applied to other problems including the design of complex training devices.

JOB BEHAVIOR FORM FOR
CHECKING AND ADJUSTING
REVISION A.
14 February 1952

AMERICAN INSTITUTE
FOR RESEARCH

NAME OF SUBTASK	CODE NO.
Adjust Picture Position and Focus	TV--1

Sheet ________ of ________

Step No.	Control Name or Description and Location	Control Action	Indicator Name or Description and Location	Indication of Response Adequacy (Give tolerance for quantitative values)	Critical Discriminations in Display and/or Decisions Required	Supplementary Actions and/or Precautions & Characteristic Malpractices
1.	OFF-ON Switch	Twist Clockwise	Switch Dial	Dial indicates ON		
2.	(Wait five minutes to warm up set.)					
3.	Channel Selector	Twist CW or counter CW	Switch Dial	Indicates "3"		
4	FINE TUNING	Twist CW or CCW	Picture Screen	Picture appears, is steady	Point in turning of dial at which picture is steadiest.	*Note: First twist knob back and forth in wide arcs through point of maximum picture steadiness; decrease range of control movement around this point until range is found within which no change in picture steadiness can be detected. Set control at center of this range.
5.	Focus Knob	Twist CW or CCW	Picture Screen	Picture changes in focus (clearness)	Leave knob at point where picture is sharpest.	
6.	Hor. Ctr.	Twist CW or CCW	Picture Screen	Picture moves so as to be in center of screen.		
7.	Vert. Ctr.	Twist CW or CCW	Picture Screen	Picture moves so as to be in center of screen.		Steps 6 and 7 may interact with Step 5. If necessary, repeat Step 5.

Fig. 1. Sample page from a Job Behavior Form.

In summary, we have seen the potential advantage of being able to predict in advance of the operational use of new equipment the job requirements for maintaining that equipment. A method has been developed for recording, with the use of Standard Maintenance Forms, activity involved in eliminating malfunctions from the prototype during its engineering tests. A method has also been provided for equipment analysis which spells out the necessary actions by the mechanic and the information available to him for guiding that action. Equipment analysis is based on the way the equipment is built and how it functions. This method may also be applied to the prototype. Job activity data and equipment analysis data supplement each other. It should be noted, however, that equipment analysis provides a more complete and probably more reliable method of determining technical job behaviors than does the Standard Maintenance Form.

Integration of Equipment Analysis And Activity Analysis

In both applications of this procedure to date, activity analysis data have been either very limited or completely lacking for the prototype. Consequently, activity data collected on the production models were not integrated with equipment analysis. It was felt that prototype and production model data should be comparable. The activity data which were collected, however, were an independent source of maintenance job behaviors for both the Q-24 and K-1. It should be emphasized that in both applications the job activity data added no *new* behaviors to those obtained from equipment analysis.

Equipment analysis provides the *sufficient and necessary* requirements for the job in question. Activity analysis, on the other hand, can provide data on what is actually done on the job. When applied at the prototype stage, activity analysis should give a preview of later field activities on production models.

In both cases where the job anticipation procedure has been applied to date, the equipment to which it was applied had been in use in the field for some time. These applications were made for the purpose of "preliminary validation" of the procedure and to determine the extent to which the maintenance job requirements could have been anticipated on those equipments. In these situations where the testing of the prototypes was completed prior to application of the procedure, the only job activity data available on the prototype were those which had been kept while that testing was going on. Unfortunately, these data were very limited in one case and completely unavailable in the other.

It was thought desirable, however, to obtain practically all available activity data on production models of the equipments. This was done. In the case of the Q-24, which was the first equipment to which the procedure was applied, malfunction problems recorded during prototype testing were compared with those obtained from activity analysis using Standard Maintenance Forms during regular maintenance operations on production model equipments. The other data obtained on the SMF's had no counterpart in prototype data, so they were used only as supplementary job analysis data on the production model Q-24. In the case of the K-1, no activity data were available from the prototype. Consequently, the activity data obtained on K-1 production models were used as supplementary production model maintenance job analysis data.

Over-all Similarities and Differences of Prototype And Production Model Maintenance For the AN/APQ-24

Checking, Adjusting, Replacing

Checking, adjusting, trouble shooting, replacing, and repairing are the five functions into which the job of line maintenance has been divided in this project. On the basis of equipment analysis a definite number of behaviors[3] is specified by each of the functions of checking, adjusting and replacing. For purposes of a summary comparison between prototype and production, therefore, these three functions were grouped together. Before presenting the results of this comparison, a little explanation about the behavior categories which were set up seems to be in order.

For these three functions alone, several thousand behaviors were specified in the analysis of the line maintenance job. It was felt that the detail and specificity of this behavioral analysis was necessary for a definitive statement of the job. However, some way of summarizing this large

[3]A "behavior" refers to a specific activity carried out by a mechanic in checking, adjusting or replacing the equipment. In addition to "motor," or manual activities, perceptual discriminations and decisions made by the mechanic also are classed as "behaviors."

bulk of behaviors is also desirable for several reasons. Briefly, the reasons are: (a) the detailed statements are too unwieldy, making it difficult to obtain an over-all picture of the job; (b) the reader unfamiliar with the equipment may be puzzled by many references to specific parts of the equipment, the connotations of technical symbols may suggest a job complexity not borne out by the job behaviors; (c) it may be desirable to abstract and generalize psychological factors which seem to be common to groups of superficially different job behaviors.

With the above reasons in mind, main area headings were set up for grouping the job behaviors. The principle that behavior, for the purpose of this research, may be adequately described by specifying the stimulus and essential discrimination or perception required, the motor response or human output required, the intervening symbolic or mental processes, and the criterion of adequacy of the response was the basis for these main area headings. The subheadings were abstracted from the behaviors in the detailed analysis.

With the specific behaviors grouped into these categories, the comparison between prototype and production was made for the functions of checking, adjusting, and replacing in line maintenance of the Q-24. This comparison is presented graphically in Figure 2.

Although there was not a one-to-one correspondence with respect to individual behavior from prototype to production model, the symmetry of these two tallies is impressive. This symmetry would support the hypothesis that with respect to the patterns and relative frequencies of the behaviors *as grouped by those categories*, the checking, adjusting, and replacing activities on the prototype are very similar to the same job functions on the production models. (More detailed comparison of these functions is contained in [3].)

In addition to the comparison of the behaviors of checking, adjusting, and replacing, test equipment used in those functions on prototype and on production models was compared. Six test instruments were common to both prototype and production model. Two test instruments were used on the prototype only, and one was unique to the production model. Training on the use of test gear used for the prototype would certainly have been appropriate for production model maintenance.

Repairing

As defined in this project, repair operations at the line level are very limited. Most of the repair work is done in the shop. Line level repair seems restricted mainly to replacement of vacuum tubes, repositioning cable plug pins, mending broken connection between wire and pin on cable plug, and replacement of dial illuminating lights and plug-in relays. Although no specific data were available on repairing of the prototype, such activities as those just enumerated are common to many different equipments. Consequently, they probably could have been foreseen at the prototype stage of the Q-24.

Trouble Shooting

The most important and without doubt the most difficult of the job functions is trouble shooting. Trouble shooting is made up of an indeterminate number of problems containing an undetermined number of steps in their solutions. It therefore does not lend itself to the same kind of behavioral analysis and comparison as the other job functions.

In order to do an analysis of this function, it was necessary to spell out a technique of trouble shooting, since no well-defined method could be found in the field. The merits of two techniques—trouble shooting by logical elimination of alternatives and trouble shooting from probability data were studied. (For a complete discussion of kinds and levels of trouble shooting and the requirements of each, see [3].)

Trouble shooting from probability data depends upon an accurate, detailed record of performance of the equipment. The maintenance mechanic, in trying to find the cause of a given malfunction symptom or group of symptoms, consults a listing of those corrective actions which had successfully eliminated the symptoms on previous occasions. He first performs the corrective action which had been successful more times than any other in clearing the trouble; that is, he takes the most probably effective corrective action. If this fails, he tries the next most probable, and so on. This method requires *reliable* tables of "probably effective corrective actions" for given symptoms. Such tables must be made from records of past maintenance work on the equipment.

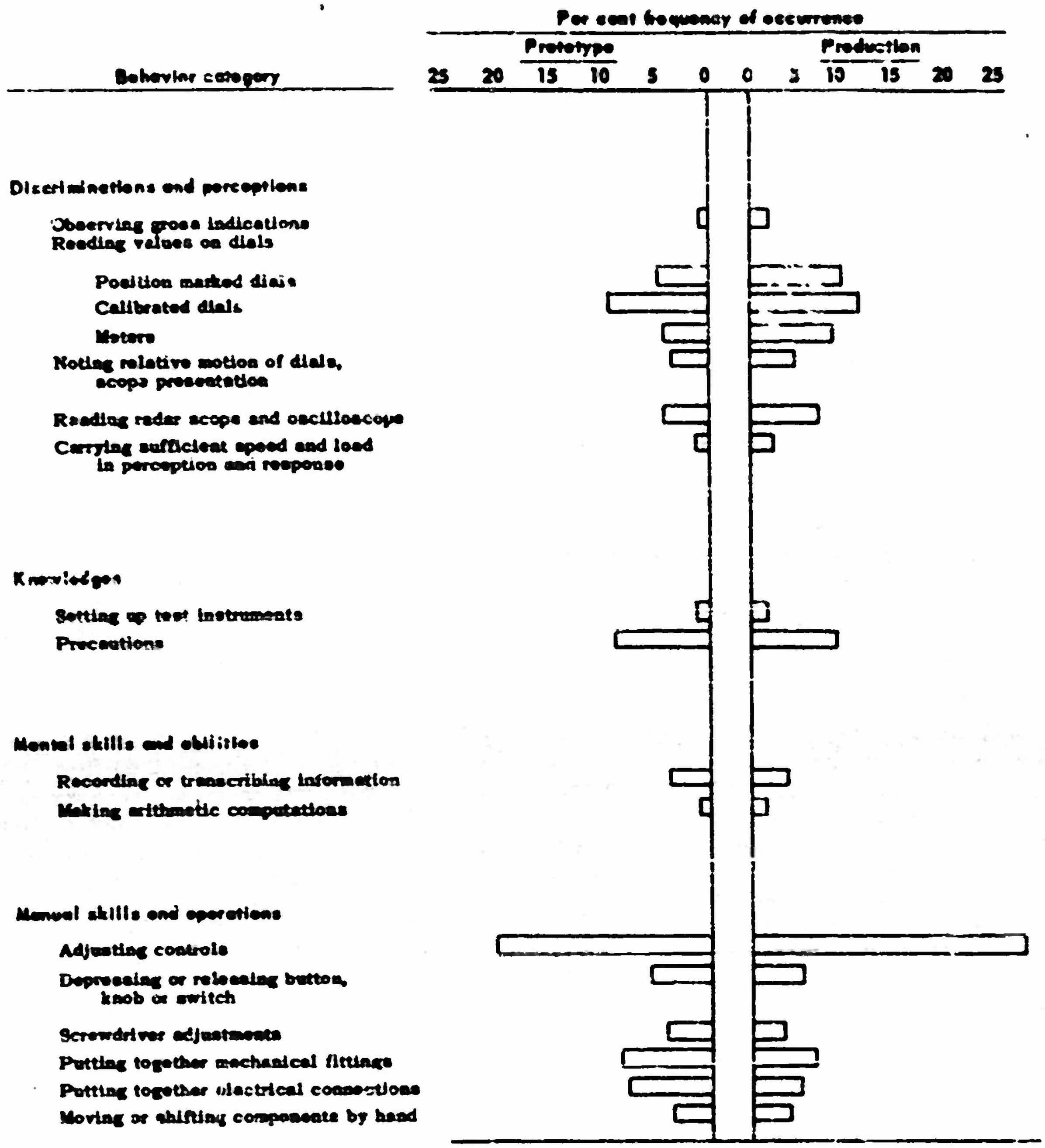

Fig. 2. Graphic comparison of categorized checking, adjusting, and replacing job behaviors: prototype vs. production model Q-24.

Because of the great number of symptoms and associated corrective actions which can and do occur, large numbers of malfunction incidents seem to be required for reliable probability tables of this kind. For example, in the case of the Q-24, 100 types of trouble-shooting problems (malfunction symptoms) were abstracted from 429 malfunction incidents (symptoms and their associated corrective actions) for the production model. These are obviously not enough incidents from which to specify probable causes for the 100 problem types. Even fewer malfunction incidents (191) were available on the prototype.

It must be concluded on the basis of these data and from the necessary requirements of a practical table of likely causes that the prototype testing will not be very helpful for trouble shooting based on probability data.

Trouble shooting, however, may also be based on a systematic method of *logical elimination of* *possibilities*, the other technique mentioned previously. This method has been judged by electronics engineering experts to be efficient as well as sufficient for localizing the cause of given malfunction symptoms. Although the logical sequence may be modified by such factors as accessibility and convenience of portions of the equipment for checking, adjusting, and replacing, the basic technique is operationally sound.

Application of this technique requires use and interpretation of the functional block diagram of the equipment; performance of rather simple logical deductions; and use of the skills and knowledges required in the checking, adjusting, and replacing functions. The degree of similarity between prototype and production for these latter three functions has been shown. The degree of similarity between prototype and production model block diagrams also bears very heavily on the over-all similarity of trouble shooting of prototype and of production models.

A comparison was therefore made between the block diagram of the Q-24 prototype and that of the Q-24 production models. This comparison showed a good many differences in the locations of test points in the equipment. With respect to *principles of operation* among or in components of the equipment *as they might affect trouble shooting by logical elimination at the line level*, however, only three differences were noted. Reducing this number to any kind of percentage would be relatively meaningless. In view of the complexity of the equipment and the large number of possible differences, however, it seems safe to conclude that these three differences do not constitute a serious dissimilarity between prototype and production model block diagrams.

This finding suggests that, in this case, line level *trouble shooting could have been taught* as a general technique and *also* as a specific skill on the Q-24 *as soon as the block diagram for the prototype of the Q-24 became available.*

Comparison of AN/APQ-24 Training and The Job Analysis

Important information about a job may sometimes be learned by looking into the basis for alleged difficulties which technical school graduates meet when they start their jobs. The difficulty, even though attributed to training, may actually lie in the assignment of personnel to training, the way in which the graduates are used, what is expected of the graduates, the incentive or motivation situation, and perhaps other causes.

In an attempt to track down the basis for some complaints about Q-24 mechanics, the Q-24 checker's course and the Q-24 systems analyst's course were compared with the job requirements of the *line mechanic*. The reader should be reminded that line mechanic functions, as here defined, consist of checking, adjusting, and trouble shooting only to the black box (subassembly plug-in) level for which the block diagram is almost always adequate. When a subassembly is diagnosed to be defective, the line mechanic plugs in a substitute replacement. The *shop mechanic*, as here defined, diagnoses and makes repairs *within* the plug-in unit which has been found to be defective.

An analysis was made of the content of the training course outlines for the checker's and systems analyst's courses. A principal finding was that the content of both these courses cuts across the line vs. shop jobs. That is, the checker's course contained classroom and laboratory content applicable in part to the Q-24 shop requirements and in part to the Q-24 flight line job requirements. The same was true of the systems analyst's course. This means that training for the specific job of line mechanic or shop mechanic was necessarily diluted.

It should be pointed out that extraneous training content adds to the difficulties of the learning and the recall of whatever critical materials need to be learned and applied to the job operations. This has both performance-on-the-job consequences and motivational consequences which may be undesirable. As more subject matter is introduced into a block of training, the trainee's rate of confusion tends to go up. If confusion tends to occur during training, it may be particularly evident in later attempts to recall the training by putting it into use in the job situation.

Thus, in the performance check and adjustment which the line mechanic does on the set there are about 840 steps involving approximately 3100 job behaviors. It will be remembered that a job behavior is a specific action unit such as a perceptual discrimination, a motor response, or a decision. It is true that all the steps and the job behaviors are not altogether independent, and the count is arbitrary in several other respects. The attempt is made here only to demonstrate that this one phase of the job alone is an extensive one. Approximately *14 hours* of the checker's course seem to have been allowed for *actual practice* in the laboratory of *a complete* performance check on a live mock-up of the set.[4] It takes a competent, experienced Q-24 mechanic between two hours and two days to do one complete performance check.

The student had some opportunity to practice check procedures on portions of the set previous to these 14 hours. However, the nature of the line mechanic's job requires that he learn the characteristics of the set functioning as a whole. Because of the many interlocking functions of the set, not only the checks and adjustments but trouble shooting at the line level requires a thorough familiarity with the equipment at the block diagram level (rather than the circuit diagram). The block diagram emphasizes and simplifies the interaction of one black box with another rather than the maze of circuits within each box. It must be concluded that additional time spent in actual practice on live mock-ups is required if the student is to become familiar with the set functioning as a whole.

Another conclusion, tentative as yet, is that a somewhat greater proportion of the time devoted to actual practice of the job behaviors in a simulated job context than is now spent would be of benefit, not only to later performance of the job, but in clarifying for the student what his training is intended to accomplish.

More can be said about this last point. Because of the admixture of training to work at the black box level and at the resistor-condenser level, it is possible that the student is not able to develop a clear idea of what his eventual tasks are going to be. This type of confusion may not only have its motivational consequences, but it may interfere with efficient orientation toward learning the job. This point is, of course, a matter of conjecture.

Disregarding the *degree* of practice given to students, the analysis of the contents of these two courses (systems checker and systems analyst) indicates that the line job is covered by the *contents* of both courses taken together. But both courses have a large amount of additional content some of which is relevant to *shop* maintenance. The total training time did not seem adequate, however, to teach one set of students both line and shop maintenance to an acceptable level of job proficiency. It should be emphasized that this requires a large amount of practice in job contexts. An actor or musician does not rush out to perform publicly after his first rehearsal without errors; rather he "overlearns" by "over-practice" to allow for inefficiencies of memory and local disturbances of various kinds.

With improved methods for anticipating the total maintenance job in specific behavioral terms, it seems possible that decisions on job division can be made more realistically. Once the total behaviors required by the equipment are specified in concrete terms, these total requirements can be broken down into patterns of individual jobs such as line mechanic or shop mechanic. The factors to be taken into account are: (1) what breakdown of the whole maintenance task will be operationally practical yet at the same time permit (2) selection and training for each job rating to be made as economically as possible while (3) providing a realistic opportunity for flexibility in reassignment to closely related jobs following on-the-job training.

These recommendations do not, however, require job specialization. Thus the operational demands and over-all job requirements may indicate that it would be most economical not to make a split into several jobs. But the decision whether or not to break down a job and how to break it down may be best made after the job requirements (and their training implications) are spelled out.

Principles in Designing Equipment for Simplicity of Maintenance

Although the preceding discussion has been directed exclusively toward the mechanic's job in maintenance, a few words should also be directed toward the design engineer's job in planning for maintenance. This is the problem of maintenance simplification. It is important to recognize three general principles which may be applied to the problem of equipment design and the mechanic's job. The first is *the design of new equipment is also the design of new jobs*. Two job areas are involved: *operating* the equipment, and *maintaining* or servicing the equipment. The more that what is known about human beings is used in the design of new equipment, the better these two jobs of operating and maintaining can be done. Until recently, in designing equipment,

[4] According to a training syllabus dated 8 April 1952, supplied by Detachment No. 1, 3303d Research and Development Group, Keesler AFB.

much more effort has been directed toward simplifying the *operator's* job than toward simplifying the *maintenance man's* job. The trend toward planned simplicity in the mechanic's job needs to be stepped up and made more systematic.

A second principle is that *even an equipment which performs very complex operations can be designed so that it is not only comparatively easy to operate but is comparatively easy to maintain.* For example, by making parts which are standard and interchangeable, strides can be made in this direction. Simple methods of testing the equipment and packaging it so as to simplify trouble shooting and replacement of defective parts are other examples.

A third principle is that *the dependability and maintainability of a new equipment in realistic field conditions should enter into the decision of whether it is desirable, from a military standpoint, to use the equipment.* That is, the manpower price should be included in the cost picture.

The research reported in these pages is concerned, at least indirectly, with methods for implementing these three principles. However, as noted previously, the major purpose of the investigation, and one with potentially immediate pay-off results, is the study of how to predict the job of maintenance mechanics on a new piece of equipment before that equipment has been manufactured in quantity.

Practical Implications

A number of primary and secondary practical outcomes of the research are indicated thus far. The realization of some of these outcomes involves more research. Others require the application of principles and techniques obtained directly from the research described herein. The general areas of these applications are summarized in the following section.

General Areas of Applications

Maintenance Mechanics Can Be Trained for Their Jobs While New Equipment Is in Production

According to various officials, both in factory training and in the Air Training Command, it would be practically unique to begin work on a training syllabus from a complete statement of job requirements. In the past these job statements have not been available. Thus persons responsible for training have had their intuitions about equipment and hunches about teaching heavily taxed.

Using the procedures developed in this project, maintenance job anticipations for equipment in pre-production stages of development could be made. These job anticipations could then be organized into training requirements. In other words, the training content of courses intended for specific equipment maintenance would be spelled out.

Job behaviors obtained in advance could also be used for the preparation of selection procedures and job-oriented proficiency criteria.

The development and tryout of training aids and devices may be undertaken concurrent with late prototype and early production stages. A clause in recent contracts with manufacturers in the development of equipment stipulates that special plans and effort will be given to working out training aids and other instructional materials. *This clause is not practical,* however, *unless the the training aids are actually relevant to the learning of the job,* and *job relevance* obviously *cannot be determined without knowledge of the job activities.* The anticipation of job behaviors can therefore provide a real basis for the design of training aids and devices early enough to allow for their timely development, and furthermore it tends to guarantee the relevance of these devices to training.

The Common Features of Radar Maintenance Job Families Can Provide the Basis for a Radar Fundamentals Course

It is generally cheaper to set up and administer one course of "fundamentals" for ten groups of specialists-to-be than to teach these same fundamentals separately to each group. This presumes that the same training materials are relevant to all the groups trained. However, it seems important to specify basic or fundamental knowledges, skills, and abilities *from job derived data and towards job directed criteria* rather than to *assume* the nature of these fundamentals in planning training courses. Thus, rather than assuming textbook theory to be a necessary part of training the mechanic, *the job activities should be studied first.* From them perhaps a job-oriented set of "general" principles can be prepared.

The Q-24 job analysis is one in a number of similar analyses which are to be made on related kinds of equipment. From these various analyses there can be found those job requirements which are common to the job family of, say, radar mechanics. From the training standpoint, these common job requirements are "basic" or "fundamental" to the job group.

One can say with confidence that one job requirement common to all technical jobs is the ability to read technical orders and translate them into job action. The more difficult the technical orders are to read and interpret, the more the training which is needed. Unless the student is able to carry in his head the entire contents of the directions in the technical orders, he will have to interpret them (or get somebody else to interpret them) when he gets on the job.

The knowledge "basic" to the design of a radar is not necessarily "basic" to maintaining it. This raises an issue which deserves at least a paragraph here. The nature and extent of training, in some cases, seems to have been determined on the basis of phrases such as, "We don't want meatball mechanics who can't do anything but follow the cookbook," rather than on the basis of concrete facts and definitions. It is easy to reply that one would prefer eating a cake baked by following a good cookbook than improvised by some kitchen chemist, but debate on this level is more a test of wit than help to the problem. There is probably agreement that what is wanted, as a minimum, is mechanics who can perform procedures according to directions and do so with rapidity, thoroughness, and accuracy. As a maximum, mechanics who were potentially able to redesign and rebuild the entire set from bailing wire and toothpicks in a few hours would be desirable.

Another kind of statement frequently heard is "A man can't or won't do a good job if he doesn't *understand* what he is doing." The joker in this sentence is the word "understand." It is true that Joe will work harder when he has work-rooted objectives and a knowledge of how his various activities lead to that objective. But this knowledge, like the answer to the question "What is sex, Daddy?" may occur at various levels and still be valid and satisfactory to the one asking the question. It is a research problem to determine what information is most easily learned by the mechanic and is most effective in getting the job done well. More rigid selection and lengthier training might, no doubt, increase the number of potential problems which the graduates can solve. But standards in these respects are already high and to push them higher would not be warranted in terms of costs unless the character of selection and training methods were first changed.

Although the present research will not by any means solve all of these problems, it is expected to provide some information to support or refute hunches as to what content should be emphasized in "basic" or "fundamental" courses.

As one system becomes obsolete, mechanics become available for transfer to a new equipment system. By showing job similarities and differences between earlier and later systems such as, for instance, AN/APQ-24, K-1, and others, a picture will be obtained on what is essential for transition training.

Preparing Technical Orders in Behavioral Terms

An ideal set of job instructions would be those exactly sufficient to enable a person knowing only the names and locations of the objects referred to in the instructions to perform, without additional help or experience, all the routine procedures of that job. This ideal may not be altogether unrealistic.

Technical orders are usually prepared by engineers. Their style, content, and format seem intended for fellow professional engineers. Theory, and details of construction and equipment action, as well as other kinds of information, surround and interlard specific instructions on what to do and when to do it. Job instructions in these technical orders, although accurate, tend to be incomplete and unclear except perhaps to one who already knows the procedures.

A complete, clearly written set of job instructions may not only supplement a training program, but in some cases it may actually take the place of training. If printed words cannot communicate, then the mechanic must learn by doing and by memorizing what to do. The performance check of one equipment may consist of several hundred steps. This takes a lot of memorizing.

The present project has developed methods of setting down job activity data on Job Behavior Forms (a sample page was provided in Figure 1). Besides serving a research purpose, this scheme may be adapted to a method of setting down maintenance instructions. Although it may seem at first glance somewhat cumbersome, the format can be quickly learned both by the writer and the reader of technical instructions. The format minimizes literary skill in composition and interpretation with a corresponding gain in clearness.

Work also needs to be done on simplifying the terminology in use. This would be a task involving major revision of current technical vocabulary.

A set of complete and clear job instructions can serve many purposes including those of training and proficiency evaluation. Most important of all, they can be a crucial instrument in simplifying learning and doing the job.

The research staff on this project is interested in further adapting and testing this promising technique of "job activity communications" to technical orders and handbooks of maintenance instructions. This work, if begun in the earliest stages of production of new equipment, can obtain two objectives with one effort. The first objective is a comprehensive job statement from which job analyses may be made for training and selection purposes. The second is, of course, a usable handbook of job instructions for both trainees and technical school graduates.

Coordinating Equipment Design and Job Design

One of the by-products of this research has been the recognition of the importance of integrating job design and equipment design at early stages of equipment development. The comparative simplicity or difficulty of the maintenance job is built into the equipment. The engineer is designing a job when he designs, for example, a radar set. The engineer should be aware of the capabilities and the limitations of the human beings on whom effective operational use of the equipment depends. There has been a great deal of research in terms of which specialists can specify, with respect to a given piece of equipment, the activities which human beings can and cannot learn to do readily and with a minimum risk of error. Specialists in human resources and in actual training should assist in planning what the equipment will be. The planning engineers may need to be reminded that the equipment will be no better than its maintenance. The manufacturer needs to be advised that he should *not* count on having engineering college graduates to keep the equipment serviced. He should count, rather, on high school graduates somewhat, but not startlingly, above average intelligence. They will probably have a number of weeks of schooling in their job but only a few hours of real practice of their job operations on actual equipment before they get placed on their jobs.

The design of testing gear and of testing procedures may also profit by assistance from human resources and training specialists in planning early in the development of the system. Thus, although the engineering psychologist and the instructor may be a nuisance to the design engineer, their criticisms and constructive suggestions on check and test points, testing gear, and packaging of the set should pay off by savings in training and other manpower requirements for maintenance.

In the course of this research some information has been collected about how to design equipment for the simplifying of maintenance. This information is by no means exhaustive of the many developments being made by various manufacturers who have been working individually on this problem. Pooling of information of this type among the services would be very beneficial.

Getting and Coordinating Information On Maintenance Activities

Another by-product of this research was the development of the Standard Maintenance Form (see Appendix A). This was a format and a procedure for getting and storing maintenance activity data, the absence of which was a severe handicap, not only to the present research effort, but also was a frequent source of embarrassment to the Air Force in solving many other problems.

An organization, like an individual, can profit from experience. In order to do so it must observe and remember information. The more accurately and completely relevant details are noted, the more reliably can the information be used in solving the next problem. But the memory system of an organization consists of its records.

Although extensive improvements have been noted in maintenance record-keeping during the past two years, attention may still with profit be directed towards the problem. Ideally, maintenance records suitably monitored and interpreted should provide data which may help the following functions:

1. Guide the modification of equipment, testing devices, maintenance, and operating procedures.
2. Design of maintenance jobs.

3. Predict job requirements in over-all maintenance of a given type of equipment when used during prototype testing.

4. Standardize and simplify recording, classifying, and filing of maintenance information.

5. Aid maintenance personnel on the line in their duties.

6. Help find bottlenecks in maintenance operations.

7. Provide criterion data for evaluating maintenance at the level of individuals, organizations, fields, and equipment systems.

Only such data should be obtained which actually will be processed and from which decisions will be made. If, however, it is decided that a given form of data will be collected, thorough indoctrination and monitoring must be given to those who note and record these data; otherwise the information will be biased, incomplete, and misleading. Most people who work with tools and instruments look on record-keeping as a nuisance chore. This attitude is fostered by poorly organized forms, requirements of excessive writing and literary effort, the belief that nothing will come of the information recorded, and finally, the indifference of supervisors.

If recording of information is to be done at all, it must be made an essential part of the job and recognized as such both by the man on the job and by his supervisor. Indoctrination must be started during training so that record-keeping gets learned as an integral part of maintenance work. But the man who keeps records must be aware and participate in their consequences if he is to remain motivated. If he sees the previous year's records stuffed in a bottom desk drawer gathering dust, he will rightly resent the red-tape paper work he has to do.

The present research has developed a format of a Standard Maintenance Form (Appendix A) which is especially intended for electronic systems but may be adapted to mechanical systems as well. The SMF has had field tryouts, but thus far only as a temporary and accessory form of record-keeping.[5] Data kept on it would assist in the seven functions mentioned several paragraphs above. Although the SMF was designed as a research instrument, it is also offered as a format for record-keeping wherever complex electronic gear is under maintenance.

[5] Details on the construction, rationale, and use of the SMF are contained in (1).

Overview and Forecast

A brief overview may help to show where this research now stands and what directions it is planned to take.

Methods have been developed for making complete, concrete statements of the maintenance job. These methods rely on an analysis of what the man must do. The analysis is based on the construction of the equipment plus data on malfunctions and corrective actions taken from maintenance activities. The technique was applied to Q-24 prototype data and compared with a similar analysis made of the production models of the Q-24 used in Strategic Air Command. The flight line maintenance jobs described by these two analyses were very similar. This suggests that actual training on specific job behaviors of Q-24 line mechanics could have been prepared and given before production models were in use.

Current and future research on other equipments will demonstrate whether specific and detailed maintenance job requirements can be similarly anticipated on them. If so, the methods for job anticipation can be recommended as a standard practice. If this is done, years of lead time in training may be saved whenever there is made a "calculated risk" that the prototype will actually go into production.

The job of maintenance can be simplified by suitable job design and division of over-all maintenance into individual jobs. These ends can in part be achieved by engineering design coordinated with job design. A revised method of setting down job instructions (technical orders) may also do much to simplify training and performance of maintenance. The present research has developed formats which may aid in this simplification program.

The stress on the collection of job data led to the design of a format called a Standard Maintenance Form. This SMF is also intended to get, with minimum effort in writing, data for diagnosing what needs to be done in set modification, training, and maintenance operations. An attempt will be made to get wider application of simple techniques for getting and processing data from prototype and field maintenance activities. It is intended later to try using the SMF for individual and organizational criteria of effectiveness.

By collecting job information on the date of several radar mechanics' jobs at various levels, it is expected to find out what elements they have in common. These "elements" will not be derived from armchair opinions such as "if they all work with electronic equipment they have to 'know' electronics." This may turn out to be true in certain ways or it may not. It is sound, at least from an economical standpoint, *to find out what actual job behaviors are common to the various jobs.* Then it can be insured that practice can be given on such behaviors in so-called "basic" or "fundamental" schools. On the basis of these common job behaviors it may be learned what "knowledge" or principles to teach the mechanic which will most effectively bring his intelligence and interest to bear on his job problems.

During the period of work on this contract there is evidence of some "spontaneous creeping" towards many of the suggestions proposed here. Through trial-and-error of manufacturers, engineering development, and technical training, these people themselves are changing in the directions proposed in this report. Research, however, speeds and makes systematic the normal trial-and-error process. It can also make results available to a wide audience rather than allowing them to stay locked in the heads of one or two people.

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Appendixes

Appendix A

STANDARD MAINTENANCE FORM

A. 1 A/C Number ____ 2 A/C Type ____ 3 Equipment ____

4 Abort ☐ Yes ☐ No 5 Scope pictures taken ☐ Yes ☐ No

2 Symptoms observed ____

4 Symptoms ... noted

☐ in flight, before bomb run
☐ in flight, during bomb run
☐ in flight, after bomb run
☐ during Performance Check
☐ during Pre-flight Check
☐ during Post flight Check
☐ during Non-routine Check

E. Line Maintenance Work

F. Adjustments Made

2 Sub or AFSC ____

1 Date | 2 Hour | 3 A/C Control Used | 4 Test Instrument Used

5 Computer-Crosshairs-Synchronization ____

6 Stabilization and Optics ____

7 Gages and Indicators ____

8 PPI and B Scope Presentations ____

9 Power and Power Supplies ____

10 Others ____

2 MOS or AFSC ____

3 Serial Number OUT | 4 Name of replaced unit | 5 Serial Number IN

A. Symptom Cleared in Aircraft

Nature of defect and

Repair work done

2 Date | 3 Hour

C5

C6

C7

C8

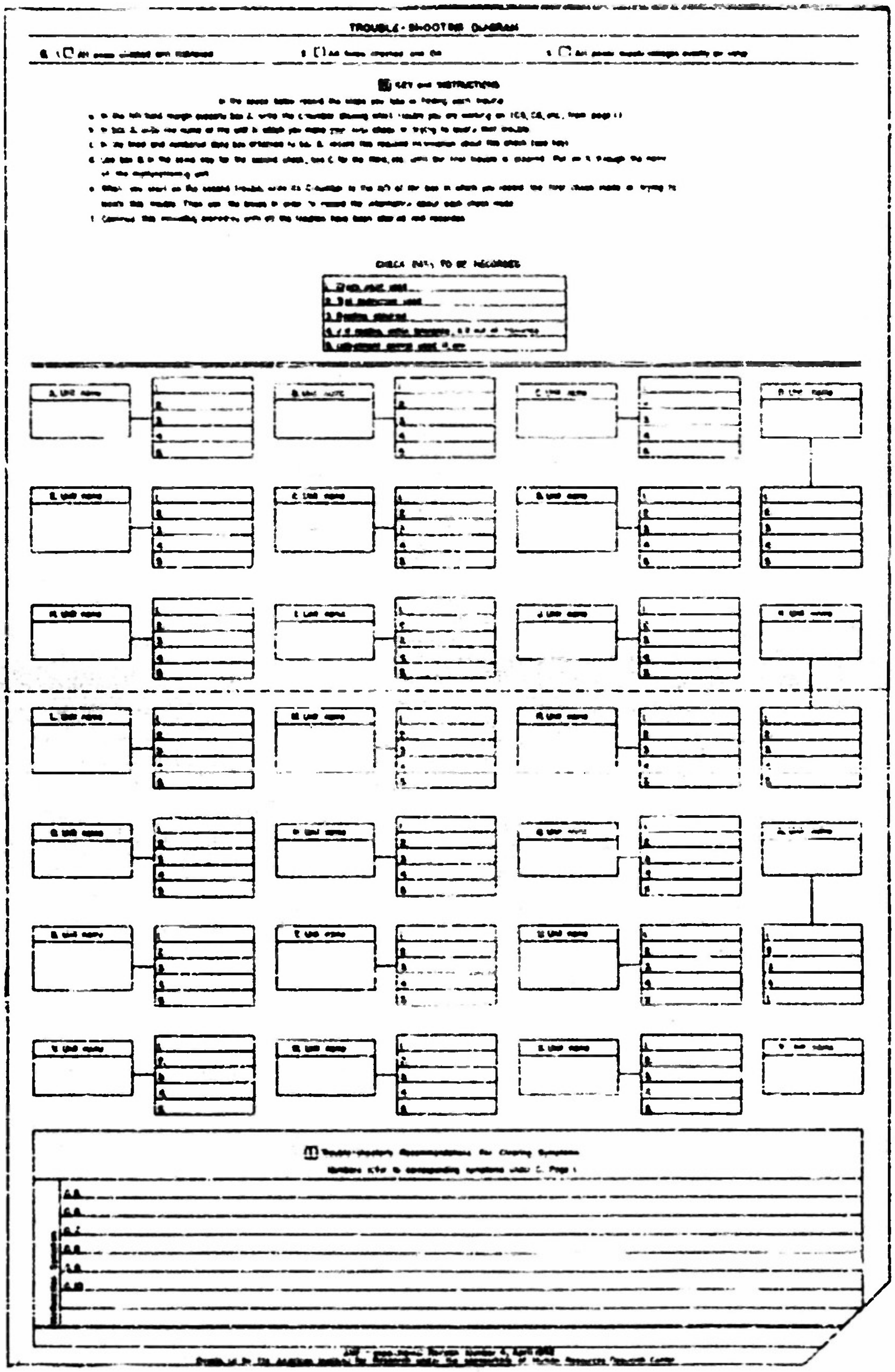
C9

C10

What would have simplified any of these jobs?

☐ Training (specify) ____
☐ Test equipment or tools (specify) ____
☐ Modification (specify) ____

2 Other comments ____


TROUBLE-SHOOTING DIAGRAM
KEY and INSTRUCTIONS
CHECK DATA TO BE RECORDED

Appendix B

An Outline of the Logic in Functional Analysis

The following steps are intended to trace broadly the relationships between the over-all purpose or objective of the equipment and the job actions which must be performed on the equipment. In other words, the "job" of the machine is shown as interlocking with the job of the man. This analysis may be carried down to extremely specific man-machine tasks. Although the present context is that of the maintenance job, the same scheme might also be applied in determining the job action requirements of the operator of the equipment.

A detailed extension of this scheme provides a basis for integrating equipment design and job design during their formative stages. It also provides for a systematic job analysis. (Note that a fictitious example is given.)

1. *What is the operational function of the equipment?* The operational objective and its limits are determined by military specifications. For example, AN/X radar bombing equipment has as its function the dropping of bombs with 50 mil accuracy on the basis of specified kinds of input information to the equipment. Fifty mils is the "tolerance limit" set for the equipment as a whole.

2. *What are the variables in the operational function which are controlled by the equipment?* These variables usually arise from natural phenomena. In equipment AN/X those variables are the variables of the "bombing and navigational problem" such as distance from target, wind direction, wind velocity, air or ground speed of aircraft, bomb ballistics, and so forth. Subsystems of the equipment control each of these variables with specified tolerance limits of accuracy. The tolerance limit of all subsystems together is determined by the tolerance limit for the operational function.

3. *What are the interaction requirements of the parts of the equipment to each other within subsystems?* This requirement is defined by the tolerance limits permitted for the specific subsystem in question. In the AN/X subsystem, for the control of "angular distance from target" the output from each component must vary within specified limits in relation to the data fed into the components of the subsystem. These equipment interaction requirements involve the engineering problems which the design of circuits and mechanisms must solve. A sample statement would be: "When shaft A is rotating at x, the changing rate of the generator must be within 2 amperes of value y or the equipment will tend not to control for angular distance from the target within allowable tolerances."

4. *What are the indicator requirements of the equipment?* These are provided by the engineering designers. They offer direct or indirect evidence of the adequacy of operation of the set and its components. For example, "When the Revolutions-per-Minute indicator is 100 plus or minus the width of the needle, the Rate-of-Charge meter must read 25 plus or minus 2 units."

5. *What are the mechanic's information requirements?* In other words, what must the set tell the mechanic so that he will know if it (or some portion) is performing adequately? This set of requirements is made up in part from what can be done by the mechanic to correct the component's action and in part from what needs to be known in order to decide whether the equipment should or should not be used in a mission. The characteristics both of the mechanic and of the equipment make up this requirement. Pointer indications on the RPM and Rate-of-Charge indicators require that the mechanic tell the difference between an in-tolerance and out-of-tolerance reading.

6. *What are the mechanic's action requirements?* What does the mechanic have to *do*, and do it *with*, and *to what*, in order that the set will operate properly? Both the equipment and the mechanic together pose these requirements. They involve the ways in which the mechanic can control the change of action of the set or portions of it. Thus, he may have a "Rate-of-Charge" adjustment screw. When he turns it to the right, the charge rate increases; when he turns it to the left, it decreases.

7. ***What are the mechanic's feedback information requirements?*** What will tell the mechanic that his attempted corrective action was adequate or inadequate? If his first response fails to be adequate, other actions which he may take to bring the needle into the correct position may be spelled out. These alternatives become subtasks in the job.

Note that steps 5, 6, and 7 tie the job of the mechanic into the job which the equipment has to perform. Steps 4 and 5 link the action of the equipment to the action required of the mechanic and are the steps where engineering design and job design come together. This is also true in Step 7. In the engineer's language, the functions of the mechanic plus the function of the equipment form a "closed loop."